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The Relation Between Microstructure and Crystallographic Orientation in Rolled Copper and Brass

H. Christoffersen and T. Leffers

Abstract The relation between microstructure and crystallographic orientation is investigated in rolled copper and brass. For the two main types of microstructure in copper (the high wall density and the low wall density structure) there is a certain relation: the orientations corresponding to a specific type tend to cluster in certain regions of orientation space. However, the clustering is not very pronounced (there is a lot of overlap), and it cannot be related to any model. There is also a certain grain-size effect: the average grain with high wall density structure is larger than the average grain with low wall density structure. For a third type of microstructure (to be described) there is a very clear relation to the crystallographic orientation. For brass the distinction is between grains with and grains without deformation twins. There is a clear trend for the grains with twins to cluster in certain regions of orientation space - regions with relatively high resolved shear stress on a twin system. But also in brass there is a significant overlap - between the orientations of grains with and grains without twins. We ascribe the ambiguities in the relation between microstructure and orientation to grain-to-grain interaction: because of the variations in the orientations of the neighbouring grains, different grains with a specific crystallographic orientation do not necessarily behave in the same way.

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1. Introduction

It is becoming increasingly clear that the microstructure of deformed metals is far more complex than the simple subgrain structure considered earlier. In the present work we deal with the microstructure of rolled copper and rolled brass. In copper rolled to moderate reductions about 50% of the grains develop a *high wall density* (HWD) structure as described in [1-6], while the other 50% develop a normal cell or subgrain structure (possibly with a high density of second-generation microbands), a *low wall density* (LWD) structure [1-3]. In brass rolled to moderate reductions about 50% of the grains contain a high density of thin twin lamellae, normally concentrated in *bundles* which are composites of twin and matrix lamellae, while the other 50% are quoted to have a rather homogeneous distribution of dislocations and no or rather few twins [7,8].

In order to come to understand the micromechanical implications of these microstructures it is an obvious first step to relate the microstructures in the individual grains to their crystallographic orientation. Leffers and Ananthan [9] attempted to do this for rolled copper and brass. To their great surprise they found that for copper the relation between crystallographic orientation and the type of microstructure was questionable. For brass there was a statistical relation but not a blatantly clear relation. In the present authors' opinion the relation between crystallographic orientation and microstructure is a very fundamental question which deserves experimental investigation under optimal conditions.

The investigation by Leffers and Ananthan was not performed under ideal conditions:

- (i) the materials investigated were rolled to reductions of 28% and 26%, which means that there were substantial lattice rotations after the type of microstructure was "decided" at lower strains (we assume that once a microstructure is established it is maintained in spite of subsequent lattice rotations)
- (ii) the results were plotted in two-dimensional inverse pole figures - and not in three-dimensional orientation space with a unique relation between position and orientation
- (iii) the TEM (transmission electron microscopy) determination of the lattice orientations was not based on the latest technique, which limited the accuracy and the number of orientations determined.

The aim of the present work is to repeat/continue the investigation of Leffers and Ananthan with due consideration to points (i)-(iii). We look at materials rolled to lower reductions (thus eliminating objection (i)). We plot the results in three-dimensional Euler space (thus eliminating objection (ii)). We use the latest technique in the determination of the lattice orientations (thus eliminating objection (iii)). Furthermore, we attempt to correlate the orientation distributions for the different types of microstructure to simple deformation models.

As a supplement to the investigation of the relation between the type of microstructure and the crystallographic orientation in copper we also investigate the relation between the type of microstructure in the individual grains and the size of the grains - by scanning electron microscopy (SEM).

2. Experimental procedures

2.1. Materials

The materials investigated were copper and brass with 15% zinc by weight produced from copper and zinc of 99.99% nominal purity. Both materials were initially (after casting in protective atmosphere) subjected to a dual deformation/recrystallization treatment (with rolling reductions about 20%) which resulted in approximately texture-free starting materials (highest orientation densities in the ODFs below two times random density) - with average grain sizes of $\sim 90\text{ }\mu\text{m}$ for copper (with a rather wide grain-size distribution) and $\sim 40\text{ }\mu\text{m}$ for brass. These starting materials were then rolled to 11% reduction for copper* and 17% reduction for brass.

2.2. TEM investigation of the effect of orientation

As outlined in section 1 the present work aims at registering the crystallographic orientations corresponding to the different components of the microstructure. The exact way in which the different microstructural components are distinguished is described together with the results in section 3.

The determination of the orientations in the transmission electron microscope (operated at 200 kV) is made according to an automatic on-line procedure developed by Krieger Lassen [10]. Convergent beam Kikuchi patterns are registered with a CCD camera and analyzed by a computer. The computer then produces a calculated Kikuchi pattern for comparison with the experimental pattern. In the few cases where the two patterns do not coincide, the operator must change the conditions in order to obtain a better pattern. This procedure normally provides very accurate orientation determinations - in relation to the sample as it is positioned in the specimen holder (see below).

The specimens are 3 mm discs cut out parallel to the longitudinal plane of the rolled plate (parallel to the rolling direction and the normal direction). This is the orientation for which the microstructures are seen and distinguished most clearly. The specimens are thinned by jet polishing in a Struers Tenupol 3 using the D2 electrolyte.

The rolling direction is indicated on the specimens, and the specimens are mounted with the rolling direction in a specific direction relative to the specimen holder - in order to refer the orientations determined to the sample coordinate system of the rolled plate. Even when great care is exerted, this cannot be done very accurately: the estimated uncertainty is $\sim 5^\circ$. One must therefore accept that there is an uncertainty of this magnitude in the final plots of the orientations as related to the sample coordinate system.

The orientations are plotted in three-dimensional Euler space with ϕ , ϕ_1 and ϕ_2 in the range $0-90^\circ$ - on the closest of constant- ϕ_2 sections with 5° intervals. With reference to the cubic crystal symmetry each grain is actually plotted as three points in Euler space (one point in subspace I, one in subspace II and one in subspace III, e.g. [11]) - with the theoretical exception of points with exactly symmetrical orientations which in practice do not appear.

* In 3.1 we also present some results for copper rolled to higher reductions in connection with the investigation of a new type of microstructure.

2.3. SEM investigation of the effect of grain size

It is possible to distinguish HWD grains and LWD grains by SEM - with the scanning electron microscope operated in the back scattering mode (at 8 kV). Therefore, SEM is a very convenient technique for the investigation of a possible grain-size effect. Examples of micrographs will be shown in 3.2.

As for TEM the HWD and the LWD structure is most easily distinguished when viewed in the longitudinal plane. Specimens cut with the surface in this orientation are ground and then electropolished in a solution consisting of 200 ml phosphoric acid, 200 ml ethylene glycol and 400 ml water. The grain sizes are determined from the micrographs. The periphery of each grain is indicated manually, and the (apparent) grain size is then calculated by the computer.

3. Experimental results

3.1. Orientation effect in copper

The typical HWD structure is shown in Fig. 1a. It is very easily distinguished from the cell structure of the LWD structure as shown in Fig. 1b (at 11% reduction there are very few second-generation microbands).

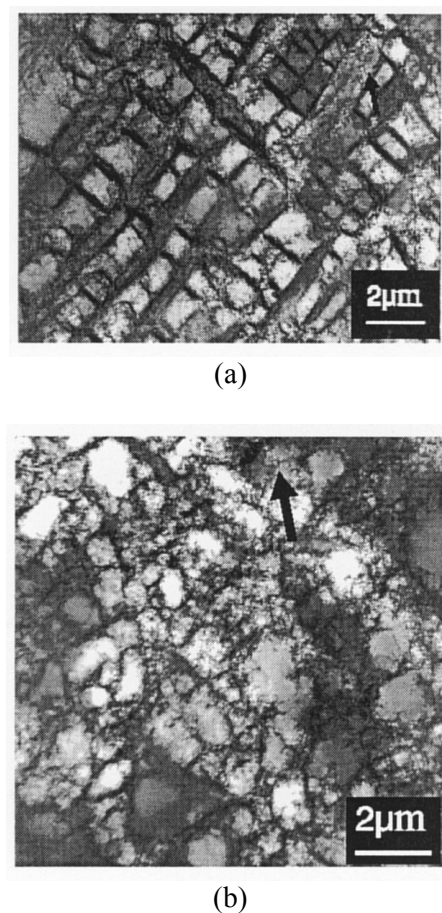


Figure 1. HWD structure (a) and LWD structure (b) in copper rolled to 11% reduction as viewed in the longitudinal section with the rolling direction indicated by an arrow.

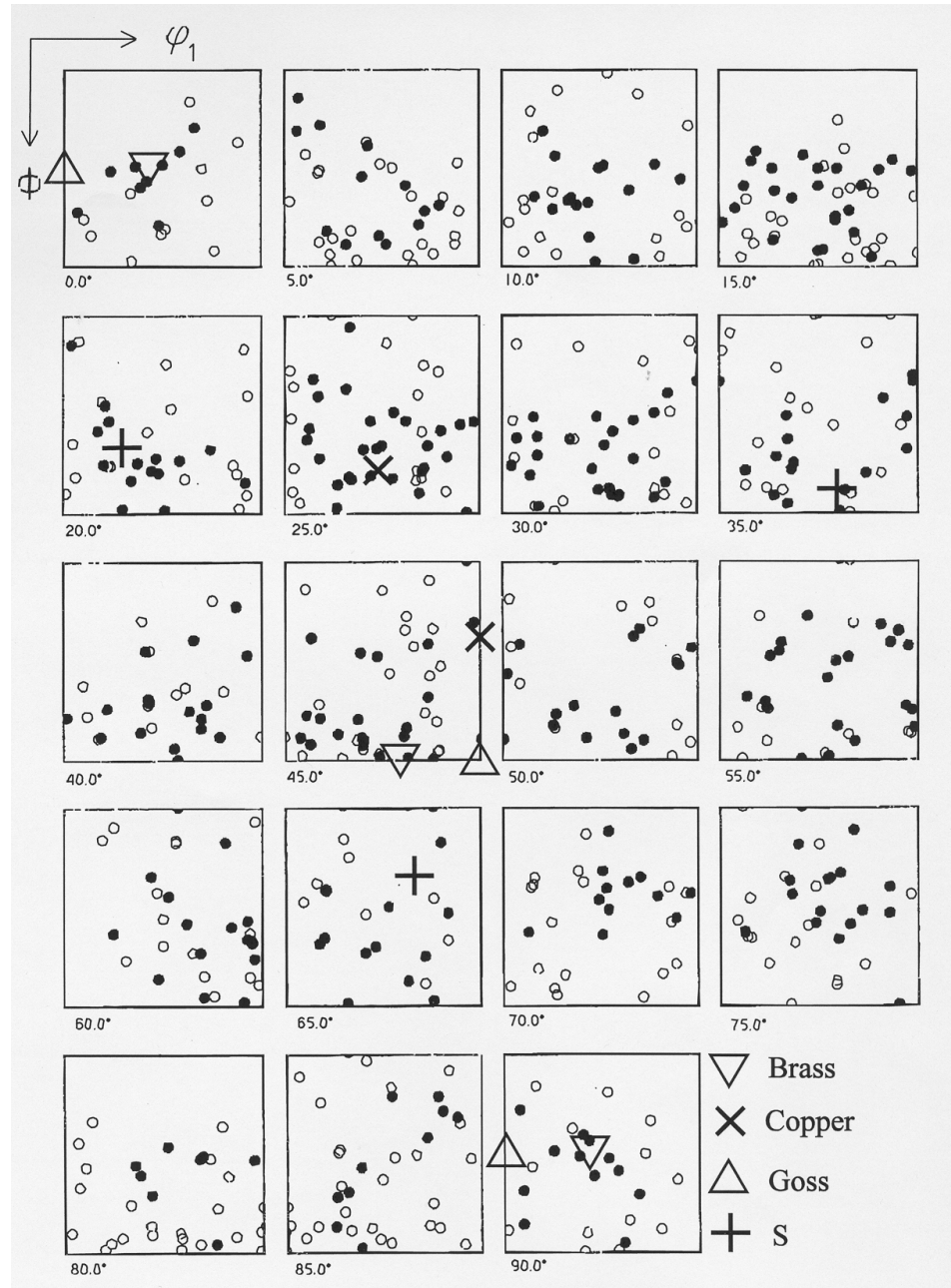


Figure 2. The distribution of HWD grains (black) and LWD grains (white) projected on constant- ϕ_2 sections with 5° intervals in Euler orientation space. Four ideal orientations are indicated (see 5.1).

The crystallographic orientation was registered for 104 HWD grains and 102 LWD grains. The results are shown in Fig. 2 (black HWD grains and white LWD grains). For comparison Fig. 3 shows approximately the same number of grains* with orientations generated on the basis of the measured texture of the copper material after 11% reduction according to the procedure described in [12] plotted in the same way as in Fig. 2. Comparison of Figs. 2 and 3 (not considering the different colours of the points in Fig. 2) shows that the grains included in Fig. 2 are a fair representation of the grains in the copper material

* For practical reasons described in [12] the number of grains in Fig. 3 cannot be prescribed exactly.

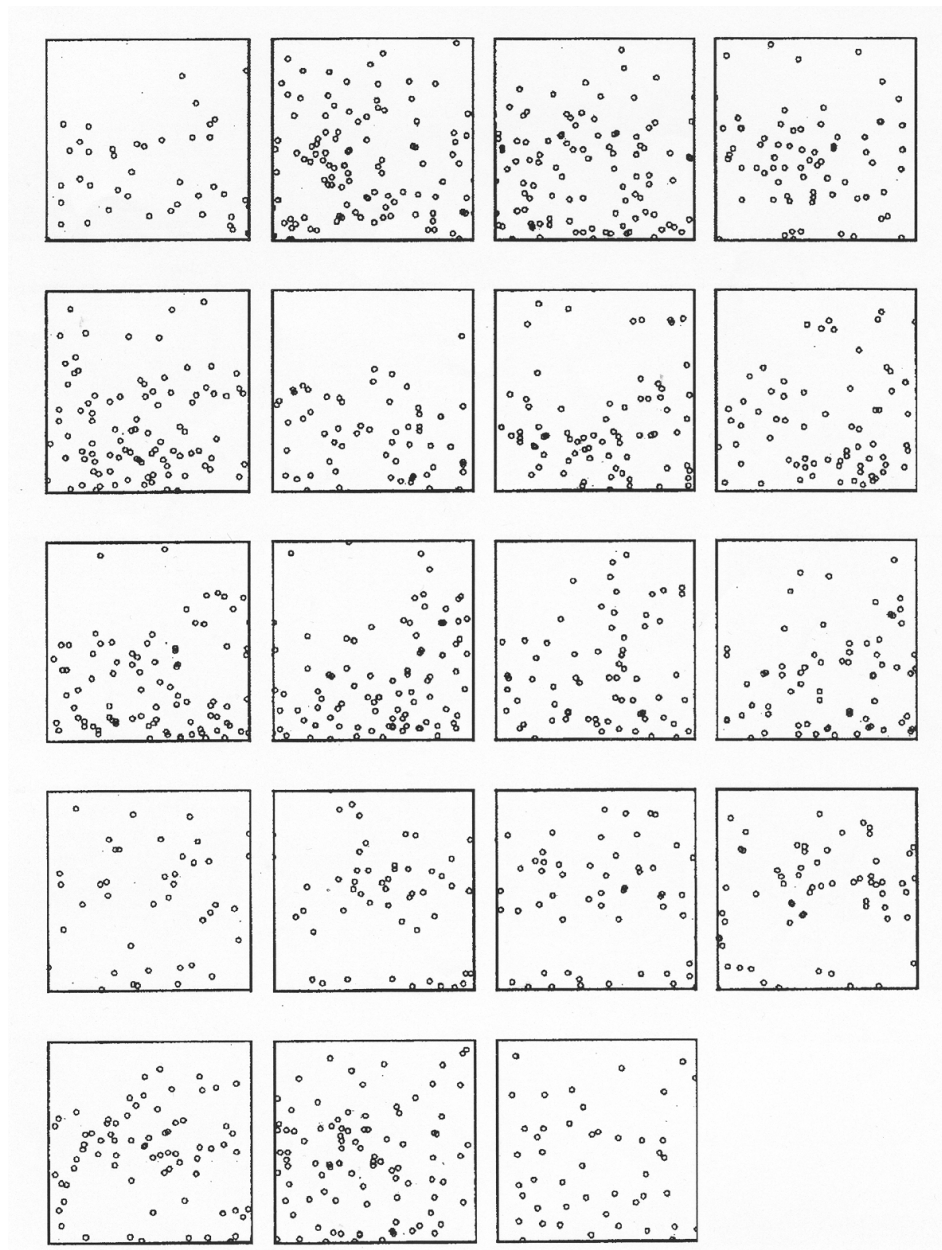


Figure 3. The distribution in Euler space of approximately the same number of grains as in Fig. 2 as derived from the experimental texture of copper rolled to 11% reduction.

rolled to 11% reduction as far as the crystallographic orientations are concerned. The uneven spatial distribution of the points in Figs. 2 and 3 is mainly due to the non-linear nature of Euler space, but there is also a certain contribution from the weak texture in the material.

Fig. 2 does not reflect an unambiguous relation between the type of microstructure and the crystallographic orientation (it does not reflect an unambiguous relation between colour and position of the points in orientation space). On the other hand there seems to be certain regions preferably populated by HWD points and certain regions preferably populated by LWD points.

In order to get an objective answer to the question whether there is a relation between type of microstructure and position we have checked the neighbour relations: does a point of a specific colour (black or white) have a point of the same colour or a point of the opposite colour as its nearest

neighbour, its second nearest neighbour and its third nearest neighbour in Euler space? The experimental fractions of neighbours with the same and with opposite colour are shown in table 1 together with the theoretically calculated fractions for random distribution of black and white points. It is evident that points of a given colour preferentially have neighbours of the same colour, but the preference is not very strong. Thus, there is a certain tendency for grains with a specific structure (HWD or LWD) to cluster in certain regions of orientation space. The detailed evaluation of this trend is to be made on the basis of the theoretical distributions presented in section 4.

Table 1. The neighbour relations for copper. NN = nearest neighbour; SN = second nearest neighbour; TN = third nearest neighbour

| Black points experimentally | | Black points random | White points experimentally | | White points random |
|-----------------------------|-------|---------------------|-----------------------------|-------|---------------------|
| NN black | 0.571 | | NN white | 0.595 | |
| SN black | 0.561 | 0.504 | SN white | 0.575 | 0.494 |
| TN black | 0.583 | | TN white | 0.631 | |
| NN white | 0.429 | | NN black | 0.405 | |
| SN white | 0.439 | 0.496 | SN black | 0.425 | 0.506 |
| TN white | 0.417 | | TN black | 0.369 | |

During the investigation of the copper specimens we realized that a few grains (or fractions of grains) had an easily recognizable third type of microstructure with very well defined cells and very small orientation differences between the cells. This type of microstructure was observed in a few cases already at low degrees of reduction (as 11%). For higher degrees of reduction the cell

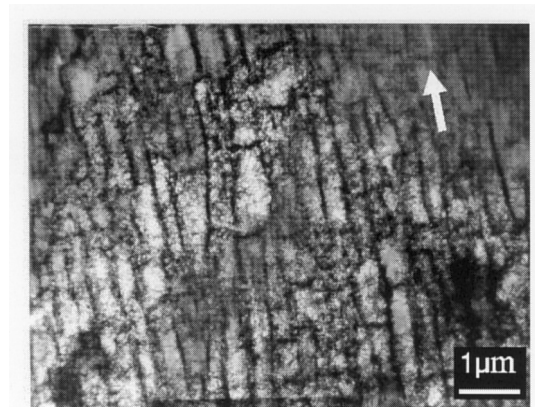


Figure 4. The microstructure with very well defined cells as viewed in the longitudinal section of copper rolled to 39% reduction with the rolling direction indicated by an arrow.

walls in this type of microstructure increasingly acquired an orientation parallel to the rolling direction as shown in Fig. 4. In Fig. 5 we have plotted the crystallographic orientations of all the regions with this microstructure which we have observed in specimens with rolling reductions of 21%-39%. All the orientations are close to (or not too far away from) the cube orientation $\{100\}\langle 001 \rangle$. Admittedly, these observations do not measure up to the principle defined in section 1, viz. that the observations should be made at low strains. However, as opposed to the HWD and the LWD structure, this special microstructure is more easily recognized at somewhat higher strains. Probably, (more difficult) systematic observations at lower strains would have produced orientations closer to the cube orientation than those in Fig.5.

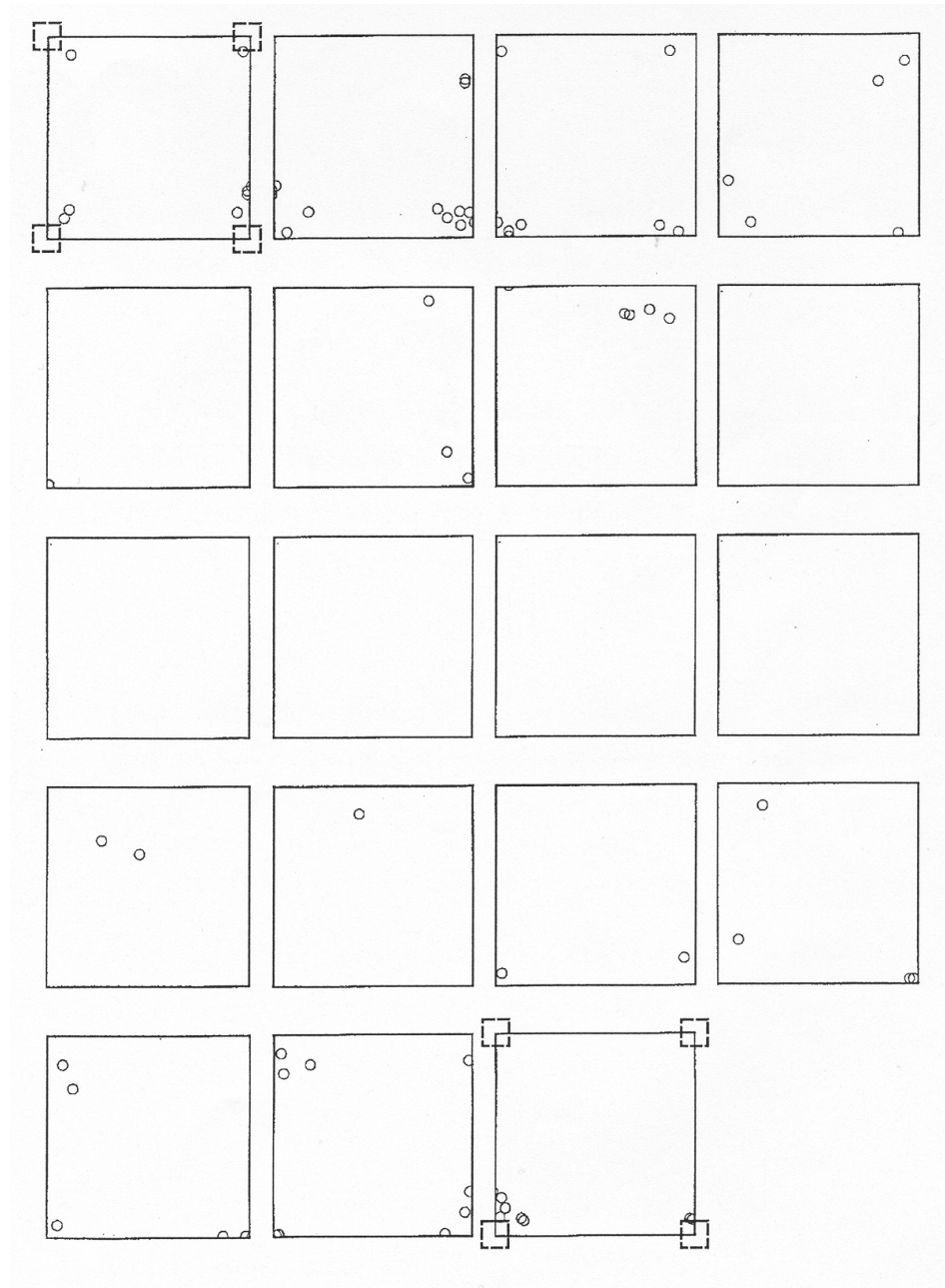


Figure 5. The distribution in Euler space of the orientations of the grains (fractions of grains) with very well developed cell structure as observed in copper specimens rolled to reductions in the range 21%-39%. The ideal cube orientation is indicated.

3.2. Grain size effect in copper

Having realized that the relation between the type of microstructure and the crystallographic orientation in copper is rather ambiguous, we decided to look for alternative ways of rationalizing the development of the two different types of microstructure. The only possibility which we in practice may pursue experimentally is an effect of grain size, cf. section 5.

Figure 6 shows typical examples of the HWD and LWD structure (the grain to the left and the grain to the right, respectively) as seen by SEM. As already stated in 2.3 one clearly sees the difference: the directionality of the dislocation walls is seen in the grain to the left whereas there is no directionality in the grain to the right.

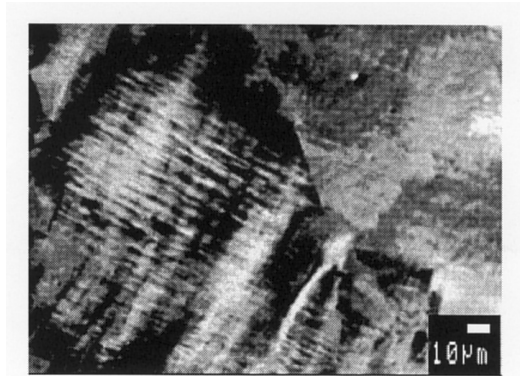


Figure 6. HWD structure (grain to the left) and LWD structure (grain to the right) as observed by SEM viewed in the longitudinal section with the rolling direction horizontal.

Figures 7a and 7b show the grain-size distributions for 102 HWD grains and for 107 LWD grains. There is a significant difference between the two distributions: the average grain size is larger for the HWD grains, and particularly the largest grains have a clear preference for the HWD structure. On the other hand there is a lot of overlap between the two grain-size distributions. Thus, grain size has a certain effect on the type of microstructure, but there is certainly not a sharp borderline between large grains with an HWD structure and small grains with an LWD structure. Grain size is just one of the factors which influence the type of microstructure.

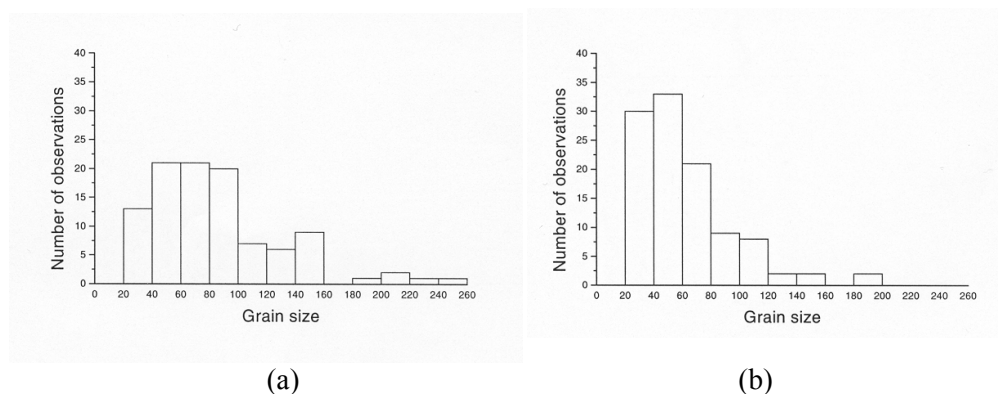
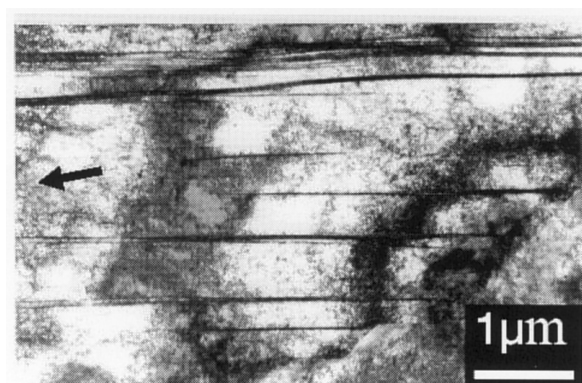


Figure 7. The grain size distributions of 102 HWD grains (a) and 107 LWD grains (b).

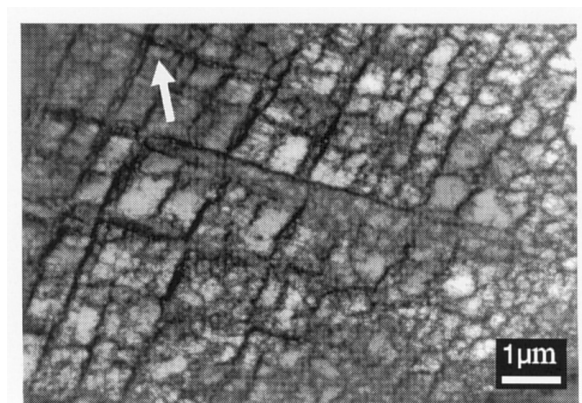
One may notice that the average grain size for the two distributions of apparent grain sizes in Figs. 7a and 7b is smaller than the grain size of $\sim 90\text{ }\mu\text{m}$ quoted in 2.1. The reason is that the average grain size from 2.1 is the true average (the apparent average multiplied by $4/\pi$).

3.3. Orientation effect in brass

In brass rolled to 26% reduction Leffers and Ananthan [9] distinguished three different types of grains: grains with bundles of lamellae of twins and matrix, grains with scattered twin lamellae and grains without twins (see also [13]). In the brass material investigated in the present work (rolled to 17% reduction) the bundle structure is not yet really developed. Therefore, the basic distinction is between grains with twins (as shown in Fig. 8a) and grains without twins. However, as opposed to earlier investigations, we have observed quite a number of grains with a structure similar to the HWD structure in copper as shown in Fig. 8b. In the great majority of cases these grains had no twins. In Fig. 9 the orientations of 81 grains with twins (black)* and 119 grains without twins (white)*



(a)



(b)

Figure 8. Grain with twins (a) and grain with HWD structure (b) in brass as viewed in the longitudinal section with the rolling direction indicated by an arrow.

* The ratio between grains with and grains without twins is not 50/50 as quoted in section 1. The quotation in section 1 refers to substantially higher reductions.

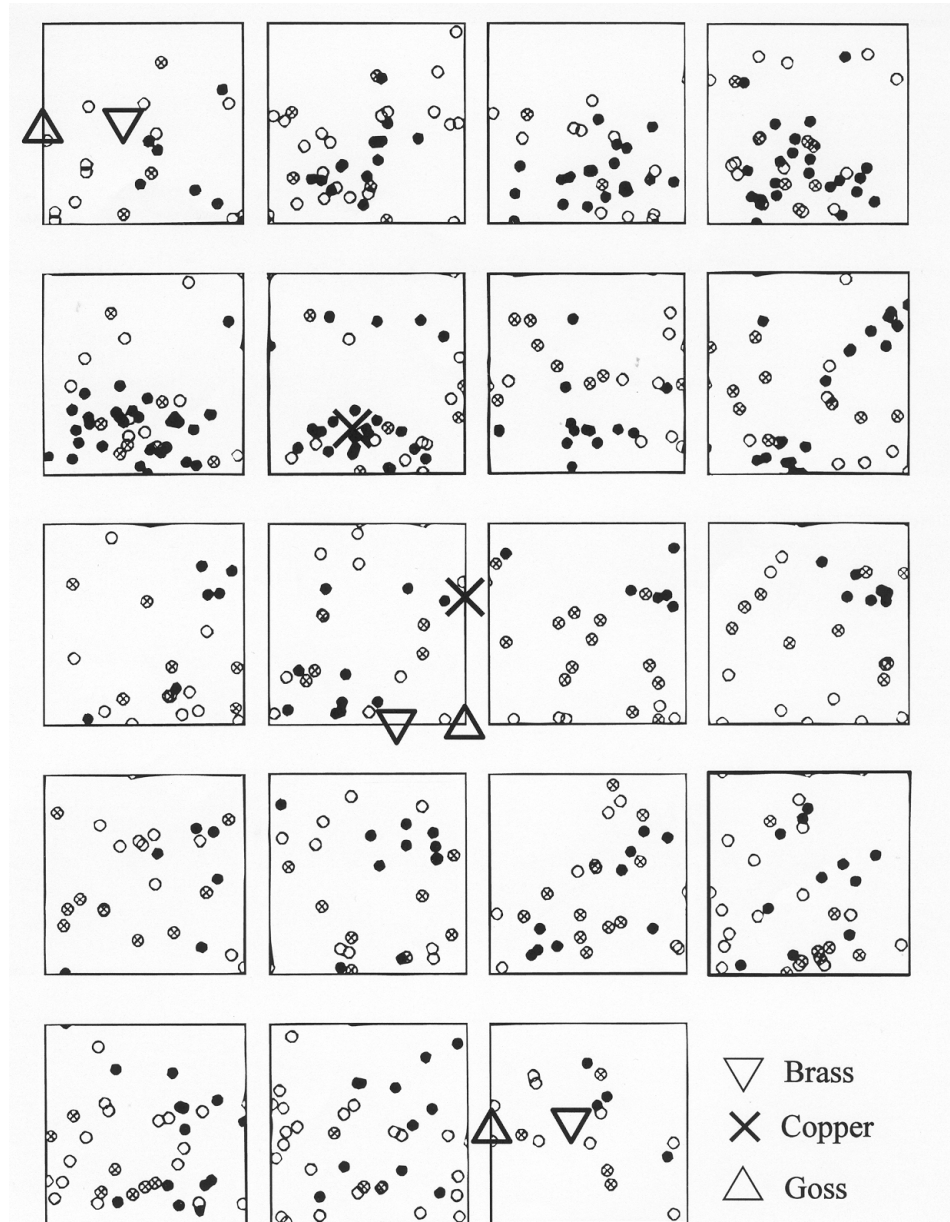


Figure 9. The distribution of grains with twins (black) and grains without twins (white) in Euler orientation space. The grains with HWD structure and no twins are singled out as white points with a cross. Three ideal orientations are indicated (see 5.2).

are plotted in Euler space. For the grains without twins we have marked those with HWD structure with a cross. A point distribution similar to that in Fig. 3, derived from the experimental texture, confirms that Fig. 9 is a reasonable statistical representation of the brass material as far as the crystallographic texture is concerned.

Figure 9 shows a rather clear, though not unambiguous, relation between twinning and lattice orientation: the black points (with twins) and the white points (without twins) cluster in different regions of orientation space. Table 2 quantifies the neighbour relations in the same way as table 1 did for copper. The

Table 2. The neighbour relations for brass. *NN* = nearest neighbour; *SN* = second nearest neighbour; *TN* = third nearest neighbour

| Black points experimentally | | Black points random | White points experimentally | | White points random |
|--------------------------------|-------|------------------------|--------------------------------|-------|------------------------|
| NN black | 0.539 | | NN white | 0.728 | |
| SN black | 0.564 | 0.402 | SN white | 0.664 | 0.593 |
| TN black | 0.560 | | TN white | 0.591 | |
| NN white | 0.461 | | NN black | 0.272 | |
| SN white | 0.436 | 0.598 | SN black | 0.336 | 0.407 |
| TN white | 0.440 | | TN black | 0.409 | |

black points have a strong preference for black neighbours as compared with the fraction of black neighbours for a random distribution. The white points have a clear preference for white points as the nearest neighbour as compared with the fraction of white neighbours for a random distribution, whereas the fraction of white points as the third nearest neighbours is close to that for a random distribution. Thus, the grains with twins clearly cluster in certain regions of orientation space while the grains without twins are *more* evenly (but not evenly) distributed.

As also stated for copper, the detailed evaluation of the relation between microstructure and crystallographic orientation is to be made on the basis of the theoretical relations derived in section 4.

For the grains with and the grains without HWD structure (white grains with and without crosses) there seems to be a certain clustering in different regions of orientation space (which has not been confirmed by statistical investigations like those in tables 1 and 2). There is no obvious similarity between the distributions of the brass HWD points and the (black) copper HWD points in Fig. 2.

4. Comparison with theoretical distributions

For the evaluation of the experimental results presented in section 3 it is essential that they are compared with distributions derived from model calculations. In this section we present model calculations referring to copper and brass, and we compare them with the experimental observations.

4.1. Models for copper

Apart from one model suggested by Leffers and Ananthan [9] there are not, in the available literature, any indications of specific deformation patterns leading

to HWD and LWD structures, respectively. We are therefore largely left to our own imagination. Intuitively we would refer to the relation between the most favoured slip system and the less favoured slip systems (considering $\{111\}\langle 110 \rangle$ systems only).

Figures 10-12 show the theoretical distributions in Euler space of regions with one slip system in a particularly favoured orientation and regions with less preference for one specific slip system. Regions with one clearly favoured slip system are white and regions without a clearly favoured slip system are grey. The borderlines are drawn in such a way that the white and the grey regions represent the same fraction of orientation space, corresponding to the fifty-fifty distribution of grains with HWD and grains with LWD structure. Figure 10 refers to a Sachs-type model, e.g. [14]: white and grey regions are distinguished



Figure 10. Theoretical distribution in Euler space of regions with one clearly favoured slip system (white) and no clearly favoured slip system (grey) as derived from a Sachs-type model for copper.

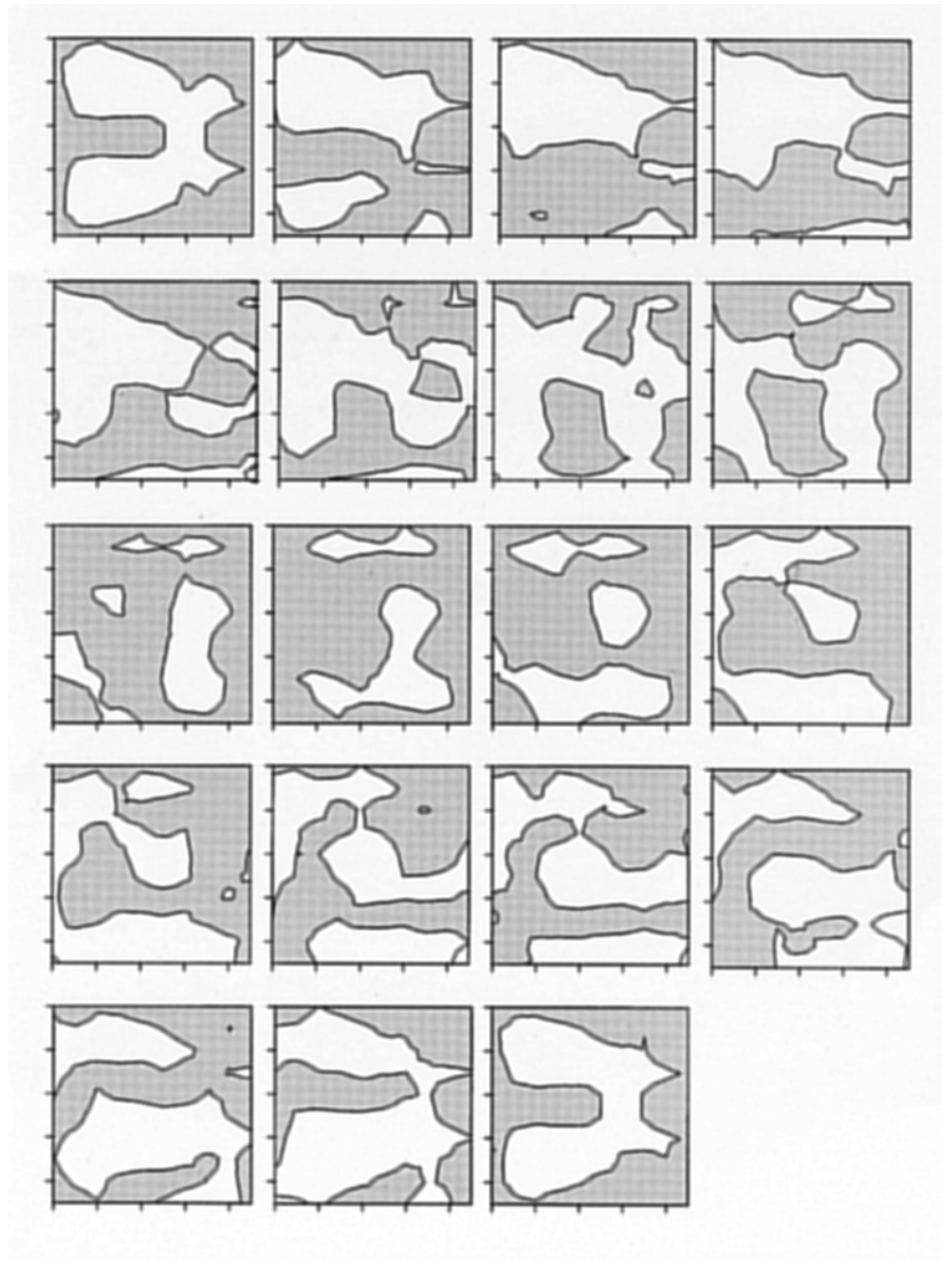


Figure 11. Theoretical distribution in Euler space of regions with one clearly favoured slip system as compared with any other single slip system (white) and no clearly favoured slip system (grey) as derived from a Taylor-type model for copper.

on the basis of the ratio between the highest and the next highest resolved shear stresses calculated from an applied stress system with tensile stress in the rolling direction and compressive stress of the same magnitude in the normal direction (a model which was also used in [9]). Figures 11 and 12 refer to the Taylor model [15]: in Fig. 11 white and grey regions are distinguished on the basis of the ratio between slip on the most active and the next most active slip systems, and in Fig. 12 the distinction is made on the basis of the ratio between slip on the most active slip system and the total slip on the other slip systems.

Comparison of the experimental results in Fig. 2 with Figs. 10-12 shows that the experimental distribution of black and white points (HWD and LWD

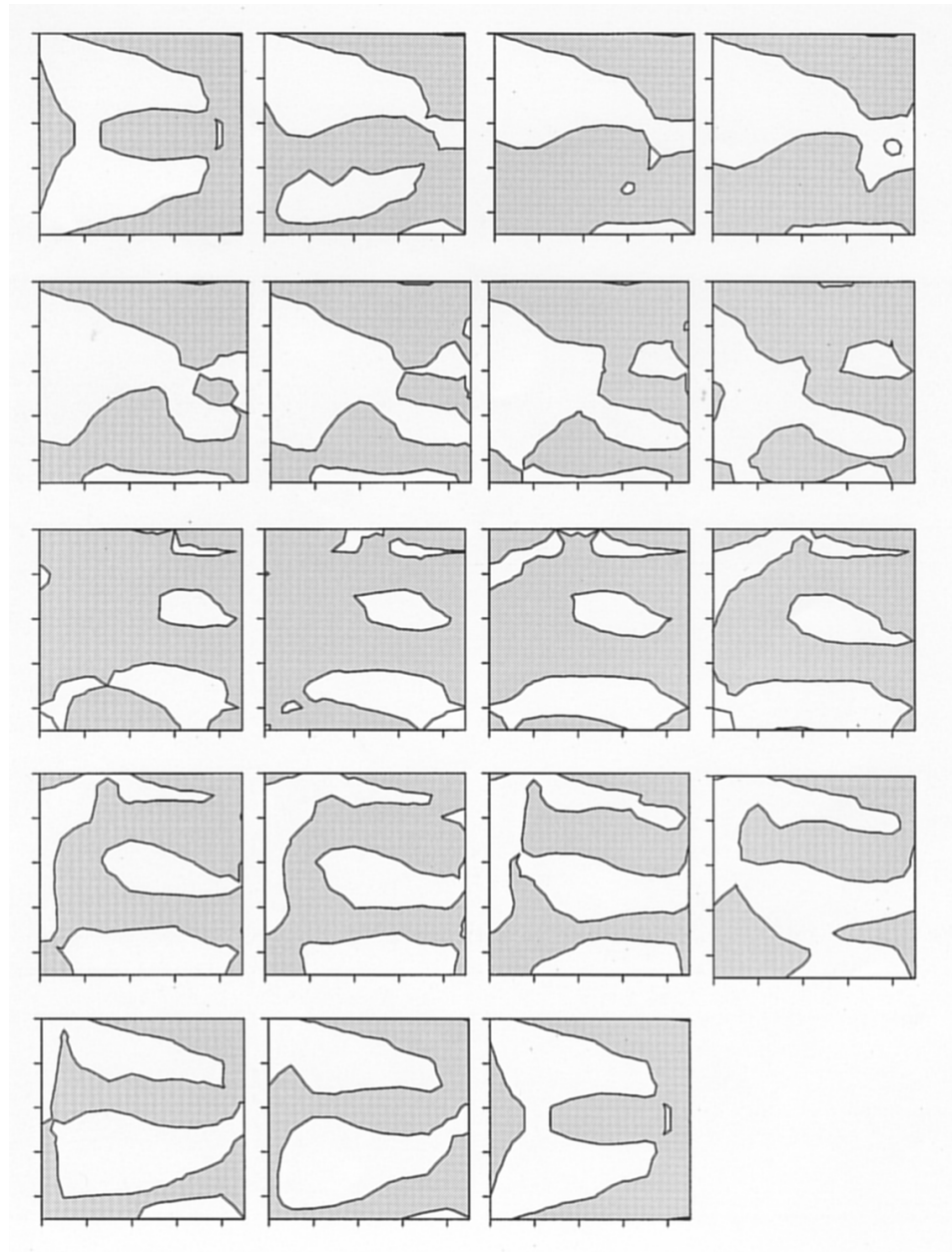


Figure 12. Theoretical distribution in Euler space of regions with one clearly favoured slip system as compared with all the other slip systems (white) and no clearly favoured slip system (grey) as derived from a Taylor-type model for copper.

points) does not correspond to any of the theoretical distributions of white and grey regions - disregarding whether one tries to correlate black points to white or to grey regions. In a somewhat different connection Winther et al. [16] have formulated various models of a type similar to that of the models used to produce Figs. 10-12. The experimental distribution in Fig. 2 cannot be related to any of the distributions of grey and white regions resulting from these models either.

One notices that the structure of white and grey regions in Figs. 10-12 is rather complex which adds to the difficulty of relating them to an experimental distribution without a clear distinction between regions with white and regions with black points as that in Fig. 2.

4.2. Models for brass

For brass the relation between the orientation of twinning systems and normal slip systems is an obvious theoretical criterion for the distinction between grains with and grains without twins - expressed in a Sachs-type [8,13,17] or a Taylor-type [18,19] model. With reference to [8,13,20] we have selected a Sachs-type model in which we make the distinction on the basis of the ratio between the highest resolved shear stresses on a twin system and a slip system (using the same stress system as in 4.1). The result is shown in Fig. 13 where grey regions

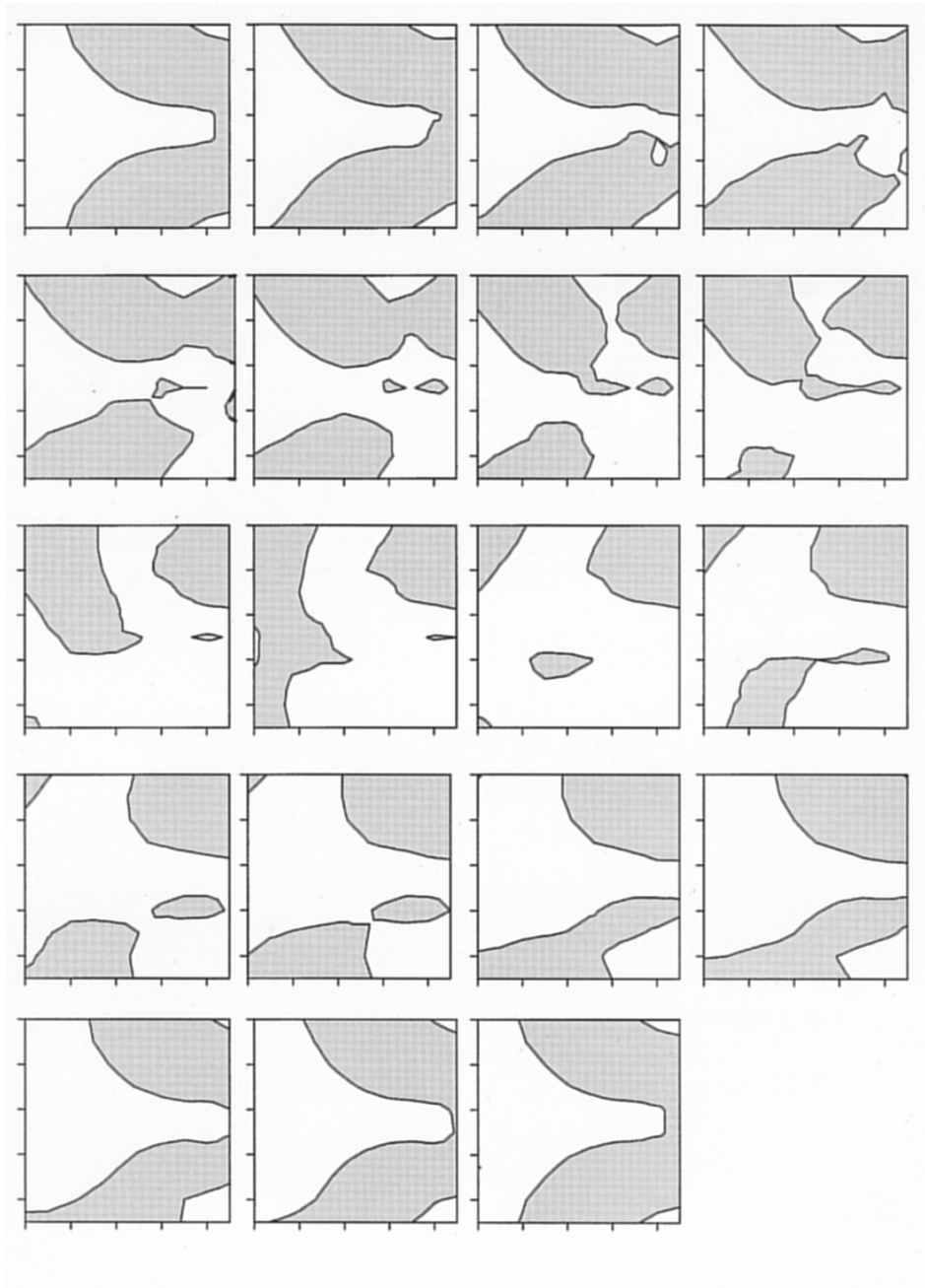


Figure 13. Theoretical distribution in Euler space of regions with a high ratio between the highest resolved shear stress for twinning and the highest resolved shear stress for slip (grey) and a lower ratio (white) as derived from a Sachs-type model for brass.

are regions with high resolved shear stress on a twin system. The borderlines are drawn in such a way that the grey regions represent 40% of orientation space, corresponding to the forty-sixty distribution of grains with and without twins.

Leffers and Bilde-Sørensen [8] (and also Leffers and Ananthan [9]) suggested an alternative criterion for the distinction between grains with and without twins (actually between grains with and without bundles), viz. the ratio between the resolved shear stresses on the most and the next most heavily loaded slip systems (with high ratios favouring twins/bundles). This is the same criterion as that used in Fig. 10, but now it must be adjusted to the forty-sixty distribution of grains with and without twins. Such a theoretical distribution is shown in Fig. 14 (with reversed colour code relative to Fig. 10).

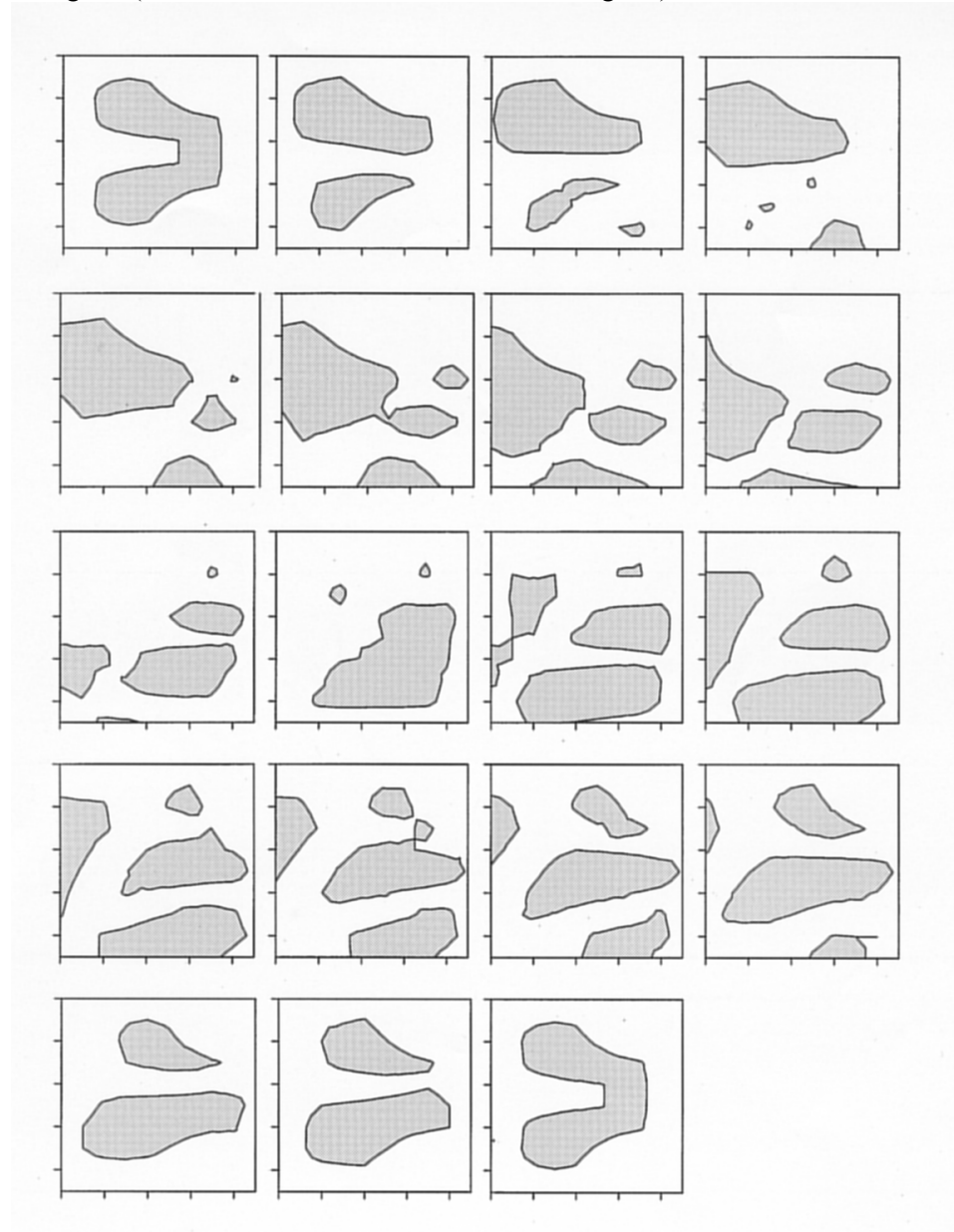


Figure 14. Theoretical distribution in Euler space of regions with one clearly favoured slip system (grey) and no clearly favoured slip system (white) as derived from a Sachs-type model for brass.

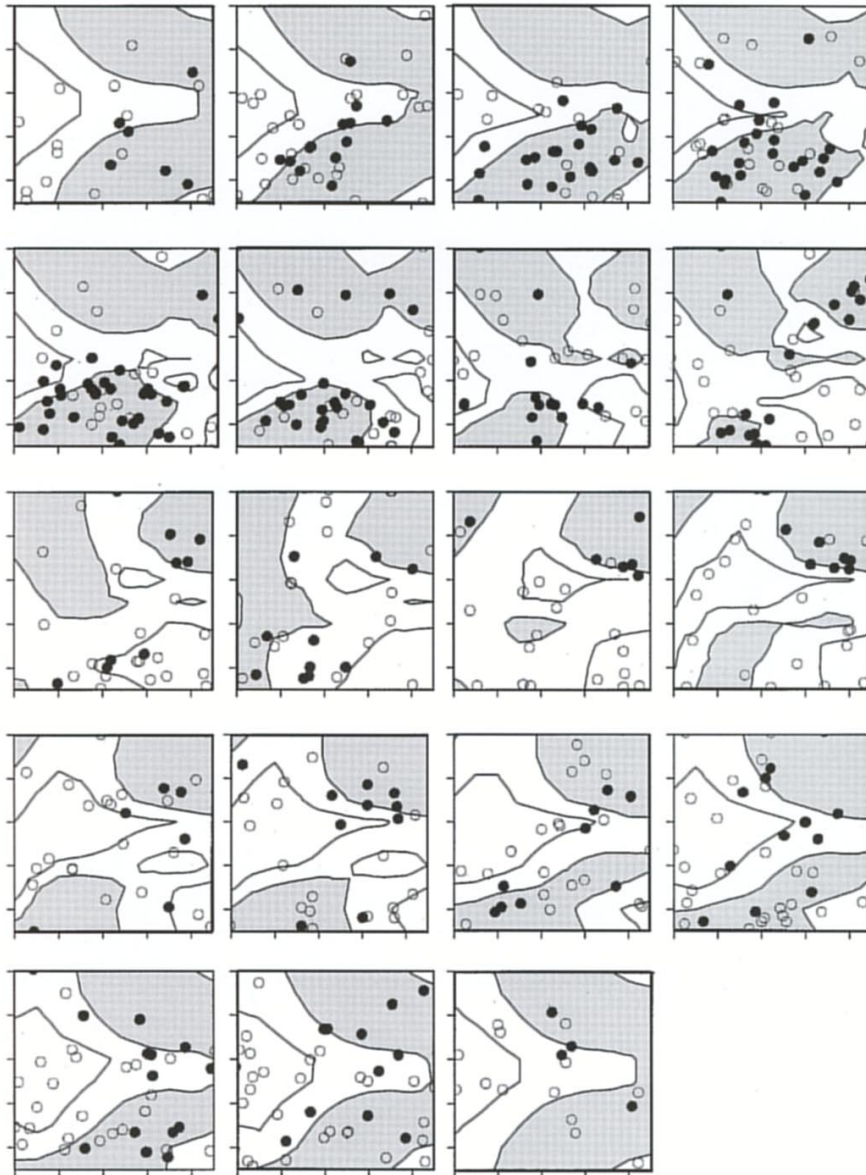


Figure 15. Superposition of Figs. 9 and 13 with an extra contour line added in the theoretical distribution.

Comparison of the experimental distribution in Fig. 9 with Figs. 13 and 14 shows that there is a clear correlation between black points (with twins) in Fig. 9 and grey regions in Fig. 13, whereas there is no correlation between Fig. 9 and Fig. 14. The correlation between Figs. 9 and 13 is demonstrated directly in Fig. 15, where the two Figures are superimposed. In Fig. 15 an extra contour line is added in the theoretical distribution corresponding to an eighty-twenty distribution of grains with relatively high and relatively low resolved shear stress on a twin system. The purpose of this addition is to show that black points (with twins) particularly tend to avoid the regions which are particularly unfavourable for twinning.

In table 3 we summarize the distribution of black and white points between the grey, the white and the “very white” regions in the theoretical distribution in Fig. 15, and we compare the experimental distribution with a random distribution. There is a clear positive correlation between black points and grey regions, a certain negative correlation between black points and white regions and a very

clear negative correlation between black points and very white regions. The white points are more evenly distributed (as already revealed in Fig. 9 and table 2), but there is a positive correlation between white points and very white regions and a negative correlation between white points and grey regions.

Table 3. The distribution of experimental black and white points for brass between the theoretically defined grey, white and very white regions and the corresponding random distribution given as fractions of the total number of points.

| | Grey regions | White regions | Very white regions |
|-----------------------------|--------------|---------------|--------------------|
| Black points experimentally | 0.250 | 0.137 | 0.020 |
| Black points random | 0.162 | 0.162 | 0.081 |
| White points experimentally | 0.204 | 0.232 | 0.157 |
| White points random | 0.238 | 0.238 | 0.119 |

One should notice that in table 3 the distribution of the total fractions of experimental points (black points plus white points) between the grey, the white and the very white regions is not exactly forty/forty/twenty (for instance the sum of the fractions of experimental black and white points in grey regions is 0.454 and not 0.400) - because the material is not ideally texture-free. Therefore one should, in reality, compare the experimental fractions with theoretical fractions which are somewhat different from the random fractions quoted. However, this would not lead to any basic change in the interpretation of table 3.

The structure of the grey and the white (and the very white) regions in Figs. 13 and 15 is simpler than that in Figs. 10-12 which will tend to make it easier to establish a correlation with the experimental distribution than it was for copper, but this is certainly not the only reason why there is a correlation for brass. The clustering of points of a specific colour in specific regions of orientation space *is* more pronounced in brass than in copper, particularly for the black points.

5. Discussion

With the experimental procedures in the present work we are able to detect correlations between the type of microstructure and the crystallographic orientation - as demonstrated for the cube-related microstructure in copper and for the grains with twins in brass. This renders credibility also to the cases where we do not observe a clear correlation: when no clear correlation is observed, there is no clear correlation.

5.1. Copper

We have observed a certain effect of grain size on the type of microstructure (HWD or LWD), but grain size is certainly not the only factor of importance for the type of microstructure. And we have observed that a structure with very well defined cells, which is not very common, corresponds to orientations close to the cube orientation. It is interesting to notice that this type of structure has also been observed in tensile-deformed copper in grains with $\langle 100 \rangle$ approximately parallel to the tensile direction [21,23]*. We do observe a certain trend for grains with HWD structure and grains with LWD to cluster in different regions of orientation space, but we could not associate this clustering with any specific model. This may be due to our limited imagination, but the trend for clustering is so weak that it probably would be impossible to establish a convincing association to any model with a level of complexity comparable to that in Figs. 10-12.

The type of microstructure developed in a specific grain must, in some way, be determined by the type of slip pattern in the grain. When this is not reflected in a clear correlation with crystallographic orientation, it must mean that grain-to-grain interaction plays a decisive role: the type of slip pattern in a specific grain is not uniquely determined by its own crystallographic orientation; the interaction with the surrounding grains with their specific crystallographic orientations is equally important or more important. This means that 1-site models [23] like the Taylor model and the Sachs model are not adequate - at least not for explaining the microstructural features. The importance of grain-to-grain interaction is substantiated by finite-element modelling of polycrystal deformation. For instance an investigation by Mika and Dawson [24] shows that the deformation pattern of a specific grain is *not* solely determined by the crystallographic orientation of the grain itself; it is strongly influenced by the crystallographic orientations of the surrounding grains. A detailed experimental investigation of grain-to-grain interaction would be very difficult (in practice impossible) for at least two reasons: (i) three new dimensions are added to the three dimensions of orientation space considered in the present work, viz. those specifying the orientation relation between a given grain and the surrounding grains, and (ii) TEM (and also normal SEM) investigations can only provide information about the (in average) 6 of the surrounding grains which are cut by the observation plane and not about the (in average) 8 of the surrounding grains which are not cut by the observation plane.

Single-crystal experiments seem to be one of the obvious solutions for future investigations into the development of the HWD and the LWD microstructures. Such experiments must give a clear orientation dependence, and hence a clue to the mechanisms for the formation of the respective microstructures. However, the complexity of the theoretical distributions (Figs. 10-12) indicate that a rather large number of single crystals should be investigated. An alternative possibility for future studies is a

* The present observation for rolled copper and the observation for tensile-deformed copper by Huang [21] were made independently.

quantitative investigation of the dislocations which form the HWD and the LWD structure. One may ask whether the formation mechanisms for the different microstructures are that important altogether. In the present authors' opinion they are: a proper understanding of polycrystal deformation must include the micromechanics and the derived microstructure.

In the last part of this subsection we shall compare our observations with single-crystal and polycrystal observations quoted in the literature - we shall examine whether certain specific crystallographic orientations have a preference for a specific type of microstructure. In such an examination one should not only look at the grains in the ϕ_2 section closest to the orientation in question (where the position of the orientation is shown). One should also look at the grains in the vicinity of the corresponding positions in the neighbouring ϕ_2 sections. The single-crystal investigations of rolled copper reported so far (e.g. [25-30]) concentrate on rather high degrees of reduction of crystals of special (symmetrical) orientations. As judged from the text and the micrographs (which were not always clear) the ordinary HWD structure (with two crossing wall systems forming angles of about $\pm 45^\circ$ with the rolling plane) as investigated in the present work was not observed under these conditions. Dislocation walls were observed in some crystals - including a "blocky cell structure" in $\{111\}\langle 110 \rangle$ crystals [27] which looks like an HWD structure rotated 45° about the transverse direction. The lacking observation of the HWD structure may be a thin-foil effect. Baker and Martin [27] reported that the wall structure dissolves in foils which are too thin (in agreement with our observations). The microstructure shown in [30] by Wróbel et al. for a $\{100\}\langle 001 \rangle$ crystal rolled to 40% reduction seems to be identical to our special cell structure.

There are only few polycrystal results in the literature with which the present results may be compared. Gil Sevillano and Torrealdea [1] quote that "Near cube orientations are specially prone to development of equiaxed cells; on the other hand rolling texture orientations seem to produce parallelogram-type cells". When one remembers that the above authors did not make any distinction between the ordinary LWD structure and the special cell structure, their first statement is in perfect agreement with our observations. In Fig. 2 we have indicated the ideal rolling texture components (represented by the brass ($\{110\}\langle 112 \rangle$), the copper ($\{211\}\langle 111 \rangle$) and the S ($\{321\}\langle 436 \rangle$) orientation). It is clear that these orientations are mainly surrounded by black points (HWD points) in agreement with the second of the above statements. The fact that we find the grains close to the copper-texture orientations to be predominantly HWD grains substantiates our statement that there is a certain correlation between the lattice orientation and the type of microstructure (but of course a correlation for a few selected orientations is of limited significance when we deal with an approximately texture-free material). Leffers and Ananthan [9] quote as the only clear crystallographic trend observed that grains with the Goss orientation ($\{110\}\langle 001 \rangle$) have LWD structure. This trend is not observed for the few points with orientations close to the Goss orientation in the present work (cf. Fig. 2 where the Goss orientation is also indicated).

5.2. Brass

In brass we observed a clear trend for the grains with twins to cluster in certain regions of orientation space - regions for which the ratio between the resolved shear stress for twinning and the resolved shear stress for slip is high (e.g. Fig. 15 and table 3) as first suggested by Wassermann [17]. It should be underlined that this does not imply acceptance of Wassermann's twinning theory for the formation of the brass-type texture (e.g. [8]). There is a certain, but far less clear, trend for the grains without twins to cluster in certain regions of orientation space. This clustering is also less clearly correlated to the grey, the white and the very white regions in the theoretical distribution (Fig. 15 and table 3). Thus, the preference for specific types of microstructure in grains with specific orientations does show clearly in brass. However the relation between the type of microstructure and crystallographic orientation is certainly not without ambiguities - indicating that grain-to-grain interaction is also important in brass. In the evaluation of the agreement or disagreement between the experimental and the theoretical distribution one must keep in mind that the theoretical distribution selected is just one of very many possibilities, and probably not the very best. On the other hand there is so much overlap between black and white points that one could never come to a perfect agreement between the experimental distribution and a theoretical 1-site distribution (not even the very best).

The establishment of a set of rules (even though not perfect) for the orientation dependence of twinning is important for the final formulation of a composite model for the plastic deformation of f.c.c. materials with low stacking fault energy, e.g. [13,31]. The model is based on the assumption that the grains with twins/bundles deform by slip on one single slip plane (that parallel to the twins), while the other grains take care of strain continuity by multiple slip.

In a significant fraction of the grains we have observed an HWD structure similar to that observed in copper, predominantly in grains without twins. It is not too surprising that there is such a similarity between the non-twinned grains in brass (deforming by multiple slip [13,31]) and some grains in copper. It is more surprising that this has never been observed before. We suggest that this is due to the foil-thickness effect first reported by Baker and Martin [27], e.g. 5.1. We have deliberately been working with rather thick foils, using an accelerating voltage of 200 kV. This is probably also the reason why the HWD structure in copper was first reported as late as 1981.

The present observations of the orientation dependence may be compared with earlier qualitative observations by Duggan and Lee [32] and Leffers and Bilde-Sørensen [8] and quantitative observations by Leffers and Ananthan [9], all referring to somewhat higher reductions. In these investigations it was found that the Goss orientation and the brass orientation normally do not have any twins - with the addition [9] that twins were never observed in the Goss orientation whereas scattered twins might be observed in the brass orientation. This is in agreement with Fig. 9, where the ideal orientations are indicated: there are only white points (with no twins) next to the Goss orientation and a majority of white

points next to the brass orientation. By comparison with Fig. 15 one also notices that the Goss orientation is in very white regions, while the brass orientation is in white regions (or close to the boundary to a white region). It was stated in [8,9,32] that the copper orientation was prone to twinning with the qualification [8] that some grains with this orientation have no twins. Again this agrees with Fig. 9: most of the points next to the copper orientation are black (with twins), but some are white.

6. Conclusions

In copper there is a certain, not very strong, correlation between the type of microstructure (HWD or LWD) and the crystallographic orientation (position in Euler space) which we cannot associate to any theoretical model. For a minor component of the microstructure, the special cell structure, there is a clear correlation to the crystallographic orientation: the orientation is always in the vicinity of the cube orientation. There is a clear relation (but not an unambiguous relation) between grain size and the type of microstructure: the larger grains have a preference for the HWD structure. We interpret the results in terms of a very strong effect of grain-to-grain interaction, i.e. we suggest that 1-site models like the Taylor model and the Sachs model are inadequate as basis for the description of the microstructural evolution during rolling deformation of copper.

In brass, grains with twins have a clear preference for certain regions of orientation space - regions with a high ratio between the highest resolved shear stress on a twin system and the highest resolved shear stress on a slip system - and grains without twins have a clear preference for regions with a particularly low ratio between the highest resolved shear stress on a twin system and the highest resolved shear stress on a slip system. But there is no sharp borderline between regions in orientation space corresponding to grains with twins and regions corresponding to grains without twins. The obvious interpretation is that grain-to-grain interaction is also important in brass, but it cannot, statistically, overrule the effect of the crystallographic orientation of the individual grains. A significant fraction of the grains in brass (largely grains without twins) develop a microstructure similar to the HWD structure in copper.

We dare to claim that the experimental procedures for the present (empirical) investigation of the correlation between the type of microstructure and the crystallographic orientation (the position in orientation space) are the best possible. When we do not find unambiguous correlations, it is because the correlations are not unambiguous. Of course one could improve the statistics by adding more points, but that would not change the basic experimental fact that there is no one-to-one correspondence between the type of microstructure and the crystallographic orientation.

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The Relation Between Microstructure and Crystallographic Orientation in Rolled Copper and Brass

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Abstract (max. 2000 characters)

The relation between microstructure and crystallographic orientation is investigated in rolled copper and brass. For the two main types of microstructure in copper (the high wall density and the low wall density structure) there is a certain relation: the orientations corresponding to a specific type tend to cluster in certain regions of orientation space. However, the clustering is not very pronounced (there is a lot of overlap), and it cannot be related to any model. There is also a certain grain-size effect: the average grain with high wall density structure is larger than the average grain with low wall density structure. For a third type of microstructure (to be described) there is a very clear relation to the crystallographic orientation. For brass the distinction is between grains with and grains without deformation twins. There is a clear trend for the grains with twins to cluster in certain regions of orientation space - regions with relatively high resolved shear stress on a twin system. But also in brass there is a significant overlap - between the orientations of grains with and grains without twins. We ascribe the ambiguities in the relation between microstructure and orientation to grain-to-grain interaction: because of the variations in the orientations of the neighbouring grains, different grains with a specific crystallographic orientation do not necessarily behave in the same way.